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Tensile behavior of New Zealand flax (*Phormium tenax*) fibers

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Abstract

The objective of this study is to characterize the tensile properties of New Zealand flax (*Phormium tenax*) technical fibers to be used as potential reinforcement in polymer matrix composites. Single fiber tensile tests were performed at three gage lengths to assess the effect of gage length on tensile strength and Young's modulus. The results were analyzed through a two-parameter Weibull distribution. The morphology, diameter, and fracture modes of *P. tenax* fibers were also characterized through optical and scanning electron microscopy.

Keywords

natural fibers, tensile behavior, New Zealand flax (*Phormium tenax*), polymer matrix composites

Introduction

Due to increasing environmental awareness, the development of the next generation of materials and processes is strongly influenced by principles of sustainability, eco-efficiency, and green chemistry.[1] The depletion of petroleum resources coupled with growing environmental regulations are acting synergistically to create a strong stimulus for new materials and products with the lowest environmental 'footprint' possible. In this regard, 'green' composites made of renewable agricultural and forestry feedstocks can represent a suitable alternative to glass fiber reinforced composites and provide potential value-added source of income to the agricultural community.[2] In order to optimize the composite properties, a detailed investigation of the mechanical properties of natural fibers is needed.

New Zealand flax belongs to the Agave family and is a monocotyledon indigenous to New Zealand and Norfolk Island. There are two distinct species of New Zealand flax: *Phormium tenax* (also known as harakeke) and *Phormium cookianum* (also known as wharariki), the key difference being the way their seed pods grow. Phormium represented an important resource in Maori life. Phormium leaves are traditionally used in the Maori culture for making plaiting mats and containers, while the extracted fibers have been used for making fishing nets, ropes, baskets, and cloaks.[3]

During the last years, several papers were published concerning the use of *P. tenax* fibers as potential reinforcement in both thermoplastic and thermosetting matrices,[4–8] but only a few papers on mechanical behavior of technical fibers can be found.[9,10] The use of *P. tenax* fibers in composites requires an understanding of the mechanical behavior of the fibers themselves, whose characterization is the principal objective of this work. The fiber strength was analyzed as a function of gage length using the Weibull statistics and the fracture modes through scanning electron microscopy (SEM) were also addressed.

Experimental

Materials

Phormium tenax (harakeke) technical fibers were collected from New Zealand. Leaves were stripped and

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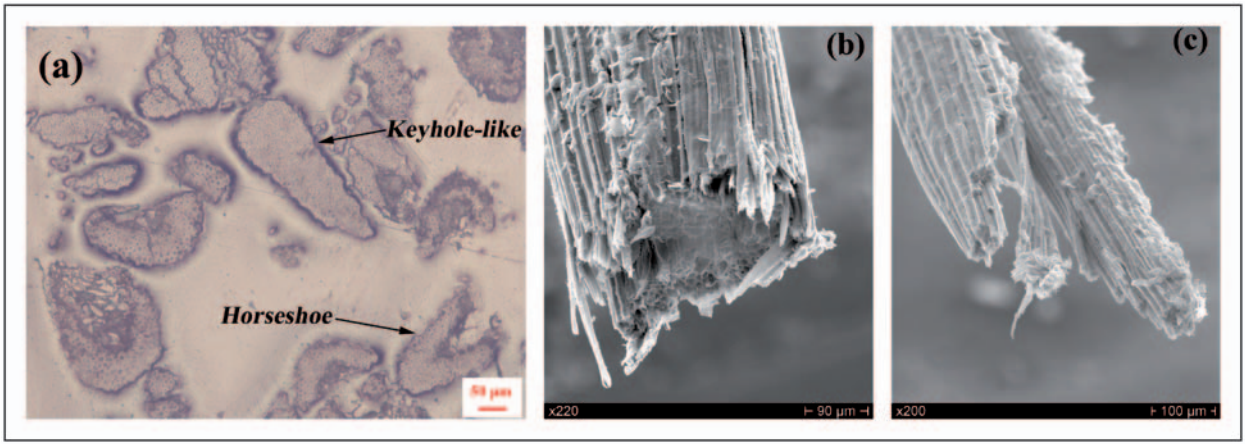

Figure 1. (a) Optical micrograph showing the cross-section of several *P. tenax* fibers; (b, c) SEM micrographs of *P. tenax* fibers fractured in tension.

the hanks of fiber were washed and then 'paddocked' (left in an enclosed area to dry) and scutched.[6,8]

Tensile tests

Phormium tenax technical fibers were mounted on a slotted testing tab according to ASTM D 3379-75. Tensile tests were carried out at room temperature on a Lloyd dynamometer LR 30 K equipped with a 20 N cell with an accuracy of 0.5%. Three different gage lengths were tested, namely 20, 30, and 40 mm, in displacement control and at a cross-head speed of 1 mm min^{-1}. For each gage length, 20 fibers were tested. *Phormium tenax* fibers, like many other natural fibers, are generally non-uniform through their cross-section and show a polygonal shape (Figure 1(a)). This poses a number of problems for tensile testing, especially when combined with variation of cross-sectional shape along the fiber length and with the splitting failure method observed in natural fibers due to their microfibril structure. A method traditionally used to overcome such problems consists in measuring under an optical microscope the average fiber diameter at five different random locations along the fiber.[11–15] The apparent cross-sectional area of each fiber is then calculated from the mean fiber diameter assuming a circular cross-section. This method was also adopted in this work and it was considered a reasonable approximation, as the objective was to study the effect of gage length on tensile properties. Nevertheless, a more detailed study to improve the accuracy of fiber cross-section determination, taking into account also the presence of the hollow structure (lumen), is under development.

All tests were conducted under standard environmental conditions (20 ± 2°C and 65 ± 2% RH).

Scanning electron microscopy

A Hitachi S-2500 SEM was used to investigate the morphology and fracture surfaces of the fibers.

Results and discussion

The fibers for the single filament tensile testing are composed of bundles of ultimate fibers having several cross-sectional shapes, which are shown in Figure 1(a), where the two most common geometries, namely *horseshoe* and *keyhole-like*,[8] can be clearly observed. As observed, the diameter shows significant variability. The average diameters of all the fibers tested are given in Table 1. In Figure 2, tensile strength values of *P. tenax* fibers are plotted as a function of their diameter, showing a decrease in tensile strength for increasing diameters, which has been reported elsewhere for other natural fibers.[11,17,22] The same behavior was also found for Young's modulus. It is to be noted that the values are widely scattered. This dispersion in mechanical properties is typical of natural fibers and represents one of the most important drawbacks.

The results of the single filament tensile tests are summarized in Table 1, where the average, standard deviation, and coefficient of variation (CV) are reported. The gage length does not seem to influence significantly the Young's modulus of the fiber. The dispersion in modulus, for a given gage length, is likely to be ascribed to the variable microstructure of *P. tenax* fibers and possible damage that occurred during the extraction process. The elongation at break of fibers decreased with increasing gage length, which is again consistent with results reported for other natural fibers.[12,23] The average strengths at different gage lengths followed the expected trend, that is, a decrease with increasing gage length. This is a direct result of

Table 1. Tensile properties of *P. tenax* and other leaf fibers

Fiber	Gage length (mm)	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Weibull mean fiber strength (MPa)	References
P. tenax	20	104.48 ± 23.18 CV = 22.19%	770.68 ± 320.52 CV = 41.6%	23.89 ± 9.45 CV = 39.56%	5.04 ± 0.80 CV = 15.75%	776.65	–
	30	135.56 ± 37.36 CV = 27.56%	579.67 ± 286.96 CV = 49.50%	27.22 ± 10.51 CV = 38.61%	3.25 ± 0.99 CV = 30.46%	569.02	–
	40	120.39 ± 26.37 CV = 21.90%	465.96 ± 214.72 CV = 46.08%	27.59 ± 12.06 CV = 43.71%	2.26 ± 0.20 CV = 8.85%	469.19	–
Pineapple	–	20–80	413–1627	34.5–82.5	1.6	–	Mishra et al.[16]
Sisal	–	50–200	468–640	9.4–22.0	3–7	–	Mishra et al.[16]
Abaca	–	122	756	31.1	2.9	–	Shibata et al.[17]
Curaua	–	66	913	30	3.9	–	Gomes et al.[18]
Henequen	–	8–33	500 ± 70	13.2 ± 3.1	4.8 ± 1.1	–	Valadez-Gonzalez et al.[19]
Fique	–	50–200	200	8–12	4–6	–	Gañán and Mondragon[20]
Banana	–	50–250	760	30.06	2.7–3.5	–	Pothan et al.[21]

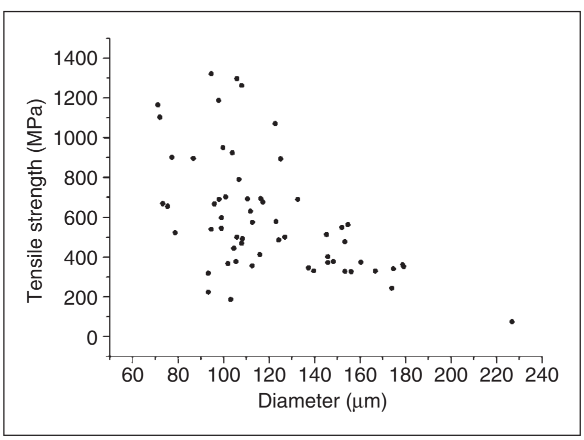

Figure 2. Tensile strength as a function of *P. tenax* fiber diameter.

the flaws contained within the fiber; fibers of longer lengths possess a larger number of defects, and therefore have more potential failure sites and a greater probability of failing at a severe flaw. As observed from Table 1, *P. tenax* fibers show mechanical properties comparable to those of other leaf fibers, whose application as a reinforcement in polymer matrices has been widely investigated.

P. tenax fibers exhibited a brittle behavior and, as Figure 2 illustrates, tensile data show a great deal of scatter, which can be attributed to the large number of flaws contained in the fibers. Due to the random occurrence of these defects, tensile strength data can be statistically analyzed. One of the most popular distributions is based on the Weibull cumulative distribution function P which accounts for dependency of strength on gage length. The Weibull cumulative distribution function P and the corresponding mean strength ($\bar{\sigma}$) are given by the following equations:

$$P = 1 - \exp\left[-L\left(\frac{\sigma}{\sigma_0}\right)^m\right], \tag{1}$$

$$\bar{\sigma} = \sigma_0 L^{-1/m}\Gamma\left(1 + \frac{1}{m}\right), \tag{2}$$

where L is the fiber length, σ_0 the characteristic strength, m the Weibull modulus, and Γ the gamma function. The parameters of the Weibull distribution were estimated through the linear regression method, using the following estimator (median rank value):

$$P = \frac{i - 0.3}{n + 0.4}, \tag{3}$$

where n is the number of data points and i the rank of the i-th data point.

The parameters of the Weibull distribution at the gage lengths tested are summarized in Figure 3(a)–(c). It is to be noted that the two-parameter Weibull distribution approximates the experimental data at each gage length reasonably well. This is also confirmed by the good agreement between estimated means for the fiber strength calculated through the Weibull distribution and the average of the raw data (Table 1).

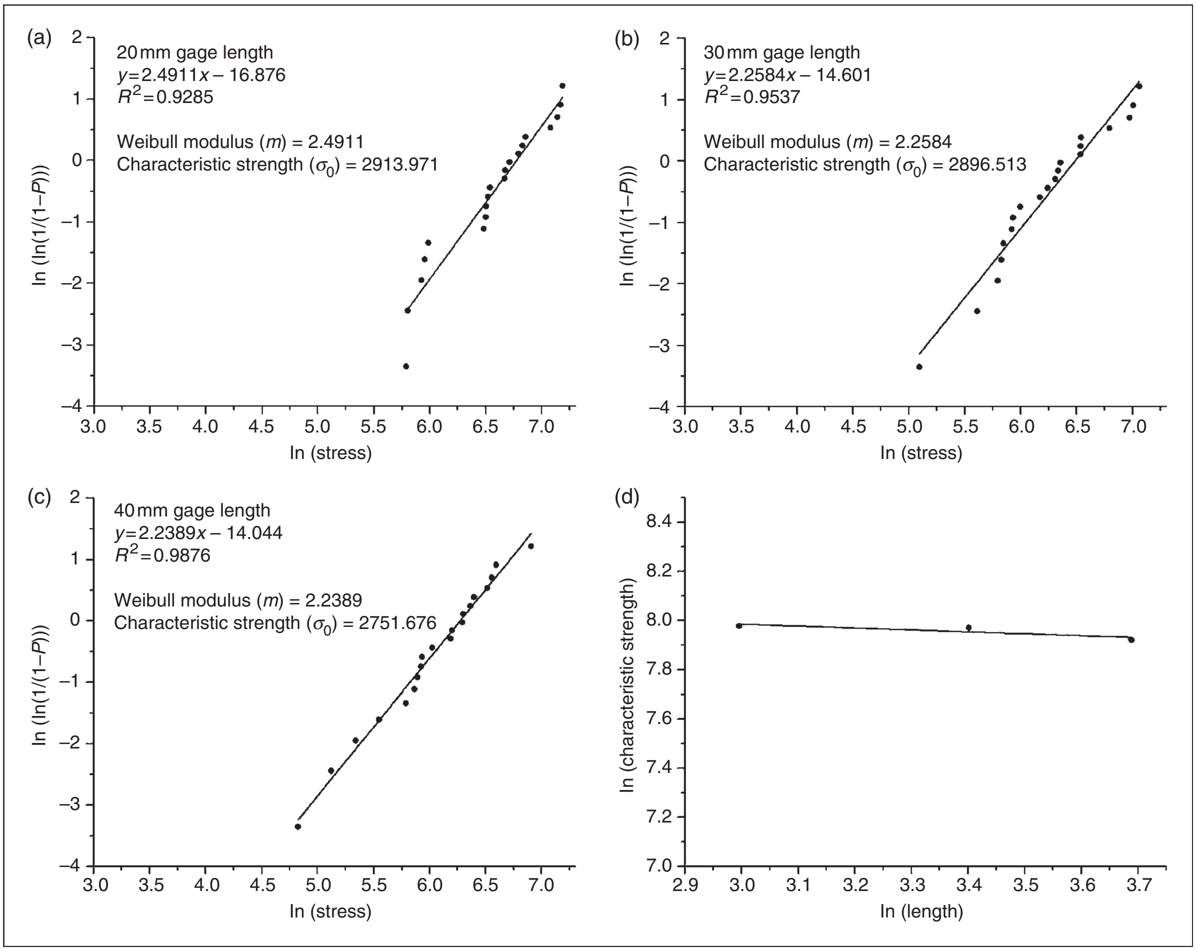

Figure 3. Weibull plots for *P. tenax* fibers tested at (a) 20 mm; (b) 30 mm; and (c) 40 mm; (d) weak link scaling plot.

According to the Weibull equation (Equation (1)), values of strength obtained at any given gage length may be used to predict the strength of a fiber for another length, for a similar probability of failure by means of the following equation[24]:

$$\sigma_{(0)2} = \sigma_{(0)1}\left(\frac{L_2}{L_1}\right)^{-1/m}, \tag{4}$$

where $\sigma_{(0)1}$ and $\sigma_{(0)2}$ are the strengths at gage lengths L_1 and L_2, respectively.

A plot of the logarithm of characteristic strength vs. the logarithm of length should give a straight line if weak link scaling is observed, from which the Weibull modulus can be obtained from the reciprocal of the gradient.[25]

The weak link scaling plot is shown in Figure 3(d). The Weibull modulus obtained from this plot was 12.8, which is quite different from that obtained for individual gage lengths. The discrepancy between experimentally calculated values and those obtained by weak link scaling from samples of a different gage length was significant, up to 28%. This suggests that weak link scaling cannot be used to scale strength obtained using fibers of a single length to predict strength at a different gage length for natural fibers. This confirms the results obtained by other authors.[12,13,25]

In Figure 1(b)–(c), SEM micrographs of technical *Phormium tenax* fibers fractured in tension are shown. Typical fracture mechanisms of *P. tenax* fibers show brittle failure of ultimate fiber cell (Figure 1(b)), while some fibers fibrillated into discrete bundles (Figure 1(c)) and the failure was not at the same stress level, thus suggesting the presence of cell wall defects along the fiber, leading to failure.

Conclusions

This study confirms that *P. tenax* fibers have sufficient tensile properties to enable using them as a suitable reinforcement for polymer composites in semi-structural applications. Albeit a good fit with the Weibull distribution function was found for single fiber strength, this did not allow for accurate scaling of strengths at different gage lengths.

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